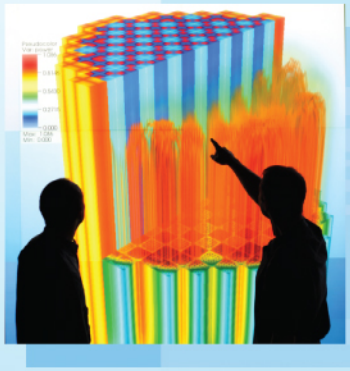
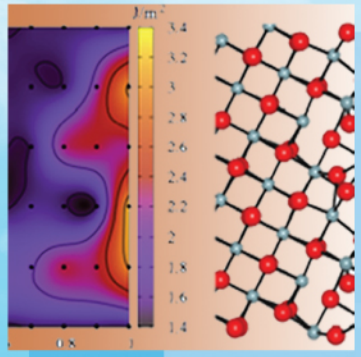
CASL-U-2014-0361-000

Power uprates and plant life extension



Engineering design and analysis

Science-enabling high performance computing



Fundamental science

Plant operational data

Consortium for Advanced Simulation of LWRs

Guest Speaker Presentation at 69th Annual Meeting of the Oak Ridge Associated Universities (ORAU) Council of Sponsoring Institutions

Doug Kothe

Oak Ridge National Laboratory

March 5-6, 2014

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

CASL-U-2014-0361-000

CASL: The Consortium for Advanced Simulation of Light Water Reactors

A DOE Energy Innovation Hub

Douglas B. Kothe
Oak Ridge National Laboratory
Director, CASL

69th Annual Meeting of the ORAU Council of Sponsoring Institutions
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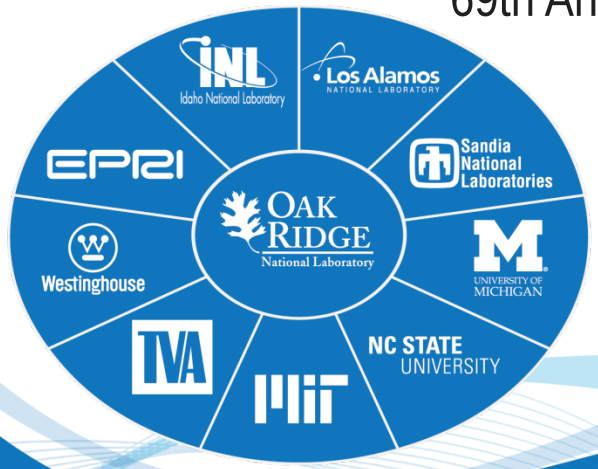


U.S. DEPARTMENT OF ENERGY
Nuclear Energy

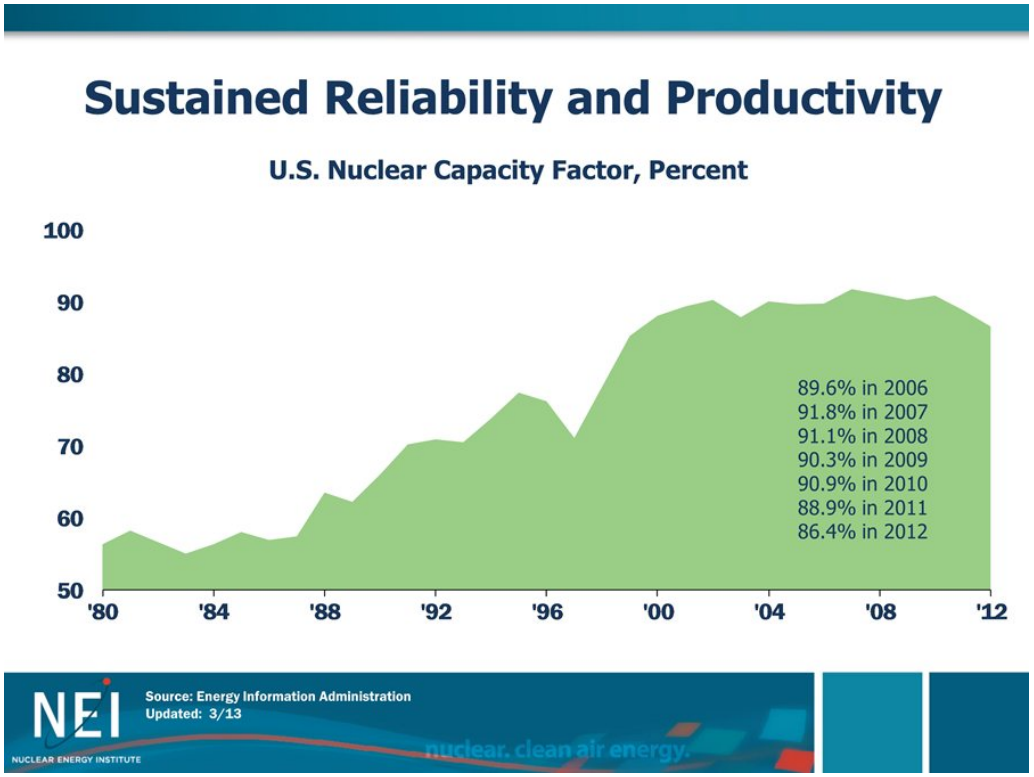
CASL
Consortium for Advanced Simulation of LWRs

CASL-U-2014-0361-000

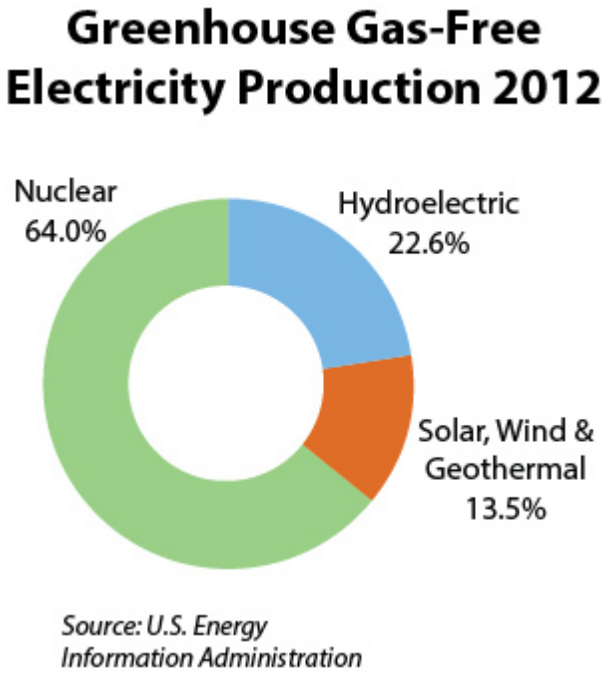
Nuclear Energy Overview

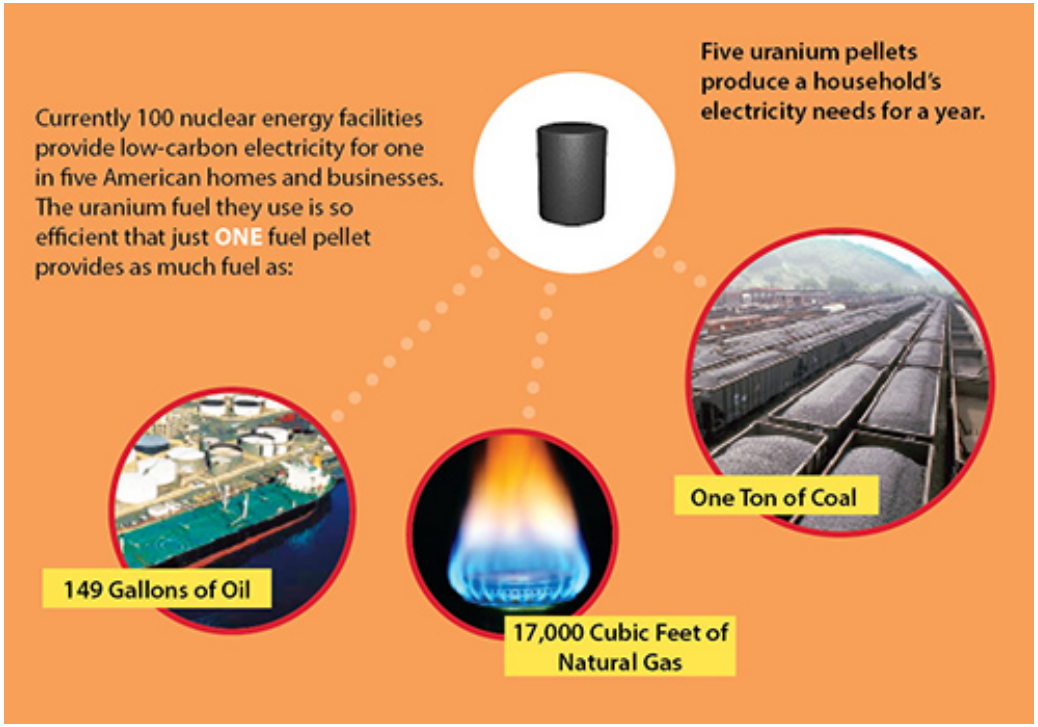
Source: Nuclear Energy Institute (NEI)

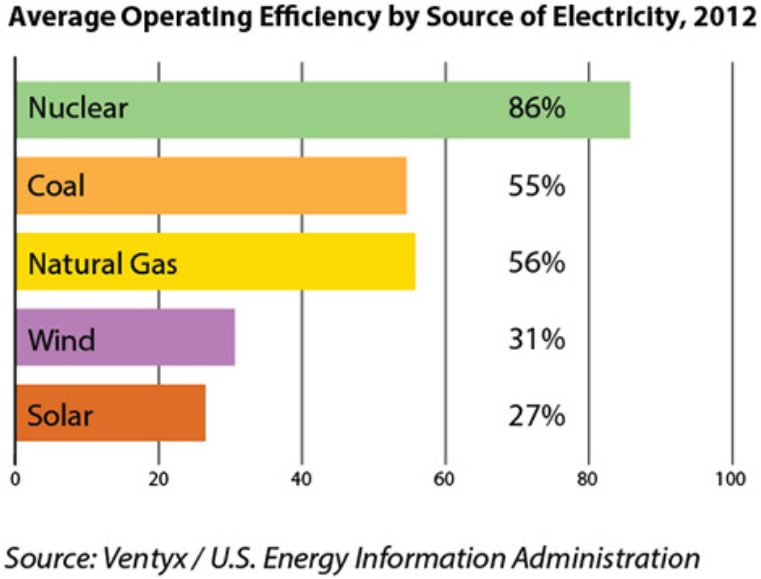
- World nuclear power generating capacity
  - 436 plants (U.S. - 100 plants in 31 states)
  - U.S. electricity generation (2012): nuclear is 0.77 out of 4.05 TWh
  - 72 nuclear plants under construction in 15 countries (5 in U.S.!)
- Electricity from nuclear: 19.0% in U.S. (12.3% worldwide)
- U.S. electricity demand projected to grow 25% by 2030
  - 2007: 3.99 TWh
  - 2030: 4.97 TWh
- Nuclear accounts for 64% of emission-free electricity in U.S.



Nuclear Energy: Clean and Reliable



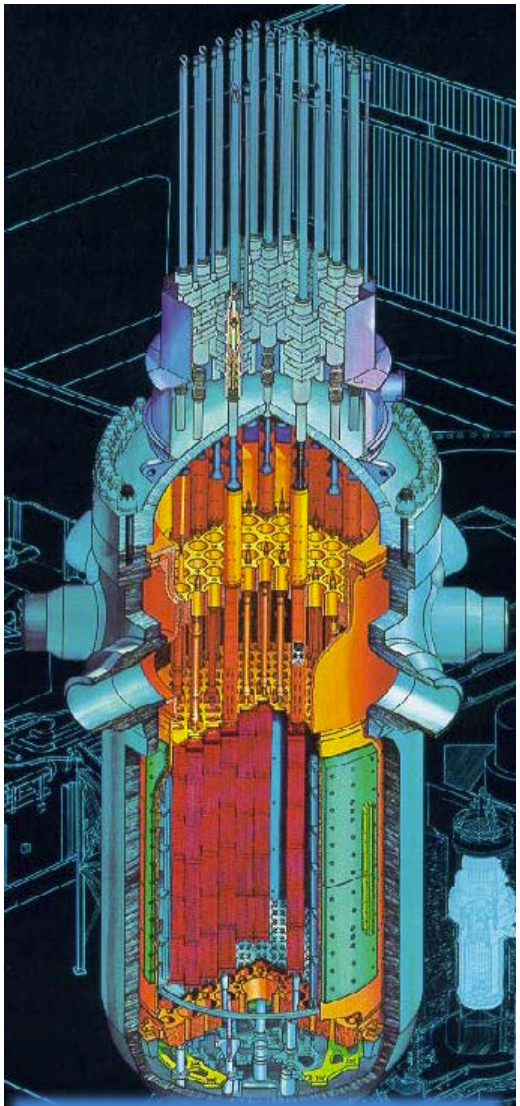




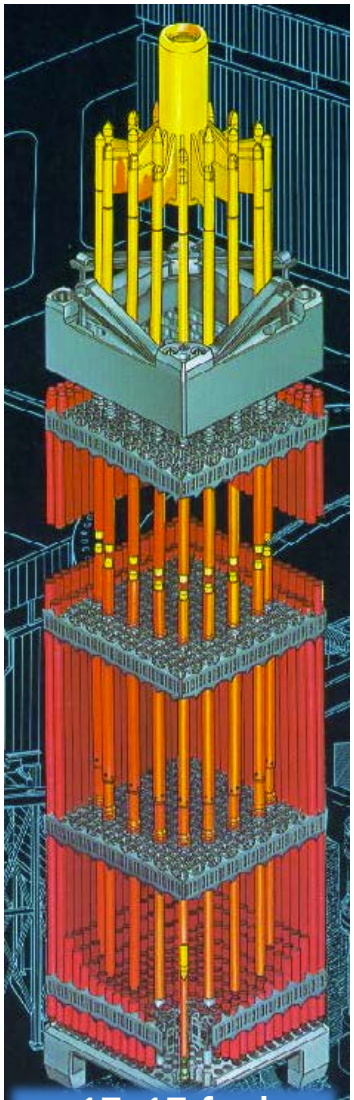
More info at nei.org (Nuclear Energy Institute)

Anatomy of a Nuclear Reactor

Example: Westinghouse 4-Loop Pressurized Water Reactor (PWR)



reactor vessel and internals



17x17 fuel assembly

Core

- 11.1' diameter x 12' high
- 193 fuel assemblies
- 107.7 tons of UO_2 (~3-5% U_{235})

Fuel Assemblies

- 17x17 pin lattice (14.3 mm pitch)
- 204 pins per assembly

Fuel Pins

- ~300-400 pellets stacked within 12' high x 0.61 mm thick Zr-4 cladding tube

Fuel Pellets

- 9.29 mm diameter x ~10.0 mm high

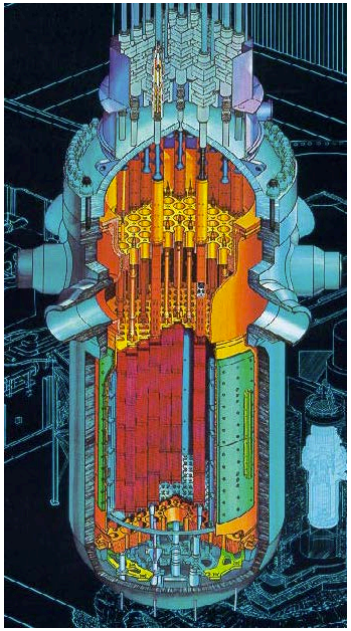
Fuel Temperatures

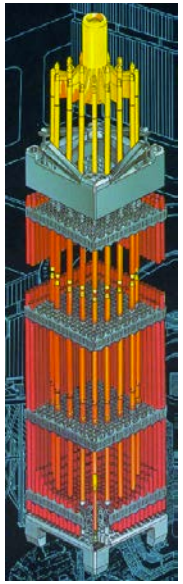
- 4140° F (max centerline)
- 657° F (max clad surface)

~51,000 fuel pins and over 16M fuel pellets in the core of a PWR!

Nuclear Energy Drivers and Payoffs for M&S technology

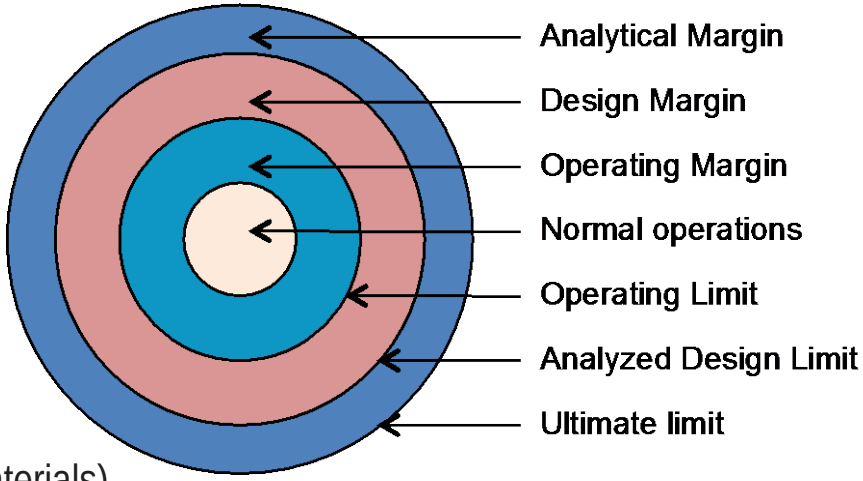
- Extend licenses of existing fleet (to 60 years and beyond)
  - Understand material degradation to reduce inspection & replacements
- Up-rate power of existing fleet (strive for another 5-10 GWe)
  - Address power-limiting operational & design basis accident scenarios
- Inform flexible nuclear power plant operations
  - Load follow maneuvering & coolant chemistry to enhance reliability
- Design and deploy accident tolerant fuel (integrity of cladding)
  - Concept refinement, test planning, assessment of safety margins
- Margin quantification, recovery, tradeoff
  - Plant parameters, fuel hardware, reload flexibility, regulatory changes
- Resolve advanced reactor design & regulatory challenges
  - Support Gen III+ reactors under construction (AP1000), refine SMR designs
- Fuel cycle cost savings
  - More economical core loadings and fuel designs
- Used fuel disposition
  - Inform spent fuel pools, interim storage, and repository decisions





M&S: An Enabler for "Margin Management"

Source: Sumit Ray (Westinghouse)



- Requires a strategic approach
  - How much is needed? How to allocate?
  - How can margin be transferred from one bucket to another?
- Key considerations
  - Plant operating parameters & assumptions (plant optimization & flexibility, load follow)
  - Fuel hardware (advanced product features & materials)
  - Design software and methodology (advanced technologies)
  - Core monitoring, In-core fuel management
  - Margins for the unknown or uncertain
  - Reload flexibility
  - Regulatory changes
- Margins can be "recovered"
  - Change in design or operation or testing, reduced safety factor
  - Reduced calculational conservatism (possibly employing advanced analytic tools)
  - Changes to design characteristics of a limiting variable
  - Decrease in the margin of one parameter to increase the margin in another
  - Modification of system or component

Margin trade-offs and evaluation of risks require involvement of many stakeholders within the Utility (Fuels and Plant Operations) and suppliers (BOP, NSSS, T/G, etc.)

One of the strategic targets for the CASL toolkit is to provide enhanced insights in the area of critical reactor margins

CASL Background

- What is CASL doing?
  - *Create* an advanced coupled multi-physics "virtual reactor" technology by adapting existing and developing new modeling and simulation (M&S) tools
  - *Effectively apply* the virtual reactor technology to provide more understanding of safety margins while addressing selected operational and design challenges of operational light water reactors
- Why?
  - Improve the performance and energy output of existing nuclear reactors by focusing on important industry defined challenge problems
  - M&S technology has long been a mainstay in the nuclear industry (vendors, owner/operators), helping to inform consequential operational and safety decisions codes daily. Current nuclear industry M&S technology, though continuously improved, has failed to capitalize on the benefits that more precise predictive capability and fundamental understanding offer (from leader to follower)
- Why do this in the Hub R&D business model?
  - Solution requires clear deliverables & products promoted by Hub R&D approach ("fierce sense of urgency")
  - Public-private partnership essential for adaptation, application, and "useful and usable" deployment of advanced M&S technologies under development at DOE national labs and universities to nuclear enterprise
- What is working?
  - Several elements have proven effective: partnerships, industry pull, technology deployment, clear deliverables and plans, effective and agile project management, 5-year time horizon, S&T guidance/review

Strong Dependency on Modeling and Simulation

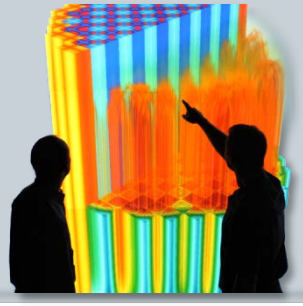
Need to assure nuclear safety but limited by inability to perform full-scale experimental mockups due to cost, safety & feasibility [1% power derating translates to $(5-10)M annual loss of revenue for 1 GWe unit]

Need to minimize economic uncertainty associated with new product introduction (e.g. fuel) by employing precise predictions [1% error in core reactivity has $4M annual fuel cycle cost impact for 1 GWe unit]

CASL's Charter

Mission is to provide leading-edge modeling and simulation capabilities to improve the performance of currently operating light water reactors

Vision	*Predict, with confidence, the performance and assured safety of nuclear reactors, through comprehensive, science-based M&S technology deployed and applied broadly by the U.S. nuclear energy industry*
Goals	• Develop and effectively apply modern virtual reactor technology • Provide more understanding of safety margins while addressing operational and design challenges • Engage the nuclear energy community through M&S • Deploy new partnership and collaboration paradigms
Strategies	• Virtual Environment for Reactor Applications (VERA) • Industry Challenge Problems • Technology Delivery • Targeted, Enabling R&D • Education and Training • Collaboration and Ideation



Scope

- Address, through new insights afforded by advanced M&S technology, key nuclear energy industry challenges
  - ✓ furthering power uprates
  - ✓ higher fuel burnup
  - ✓ lifetime extension

  while providing higher confidence in enhanced nuclear safety
- Focus on performance of pressurized water reactor core, vessel, and in-vessel components to provide greatest impact within 5 years

CASL Components

US team with a remarkable set of assets – Address tough industry challenges that matter – Urgent and compelling plan

Collaborate creatively – Target and foster innovation - Deliver industry solutions with predictive simulation

CASL Must Embrace the Broad Nuclear Enterprise

Core partners

Oak Ridge National Laboratory

Electric Power Research Institute

Idaho National Laboratory

Los Alamos National Laboratory

Massachusetts Institute of Technology

North Carolina State University

Sandia National Laboratories

Tennessee Valley Authority

University of Michigan

Westinghouse Electric Company

Contributing Partners

ASCOMP GmbH
CD-adapco
City College of New York
Florida State University
Imperial College London
Rensselaer Polytechnic Institute
Texas A&M University
Pennsylvania State University
University of Florida
University of Tennessee – Knoxville
University of Wisconsin
University of Notre Dame
Anatech Corporation
Core Physics Inc.
Pacific Northwest National Laboratory
G S Nuclear Consulting, LLC
University of Texas at Austin
University of Texas at Dallas

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

A Different Approach

- "Multi-disciplinary, highly collaborative teams ideally working under one roof to solve priority technology challenges" – *Steven Chu*
- "Create a research atmosphere with a <u>fierce sense of urgency</u> to deliver solutions." – *Kristina Johnson*
- Characteristics
  - Leadership – Outstanding, independent, scientific leadership
  - Management – "Light" federal touch
  - Focus – Deliver technologies that can change the U.S. "energy game"

Nuclear Energy M&S Applications Must Support a Wide Range of Spatial and Temporal Scales

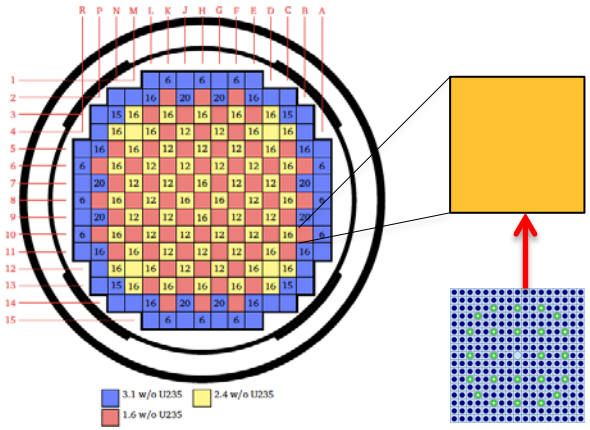
- Nuclear fuel behavior and performance
  - Spatial scale: fuel pellet to fuel pin to fuel sub-assembly (3x3 pins)
    - From dislocations/voids/cracks (< 1 μm) to grains (<100 μm) to clad (<1 mm) to pellet (<5 cm) to pins (<4 m)
- Single-phase thermal hydraulics
  - Spatial scale: fuel sub-assembly (3x3 pins) to fuel assembly (17x17 pins)
    - From mixing vanes (<1 mm) to boundary layers (<1 cm) to turbulent structures (<10 cm) to assemblies (5 m)
- Multi-phase thermal hydraulics
  - Spatial scale: fuel assembly (17x17 pins) to full core (193 assemblies or >51K pins)
    - Same as single phase except now add bubbles (<1 mm to 1 cm) and full core (<10 m)
- Neutron transport
  - Spatial scale: fuel pellet to fuel pin to fuel assembly to full core; also 2D lattice
    - From burnable absorber layers (<1 mm) to pellet (< 1 cm) to lattice (<1 m) to full core (< 10 m)
- Coolant chemistry and CRUD deposition/buildup
  - Spatial scale: fuel pellet to fuel pin to fuel subassembly(?)
    - From oxide/hydride layers (<10 μm) to CRUD layers (< 0.1 mm) to pellets (<5 cm) to pins (<4 m)

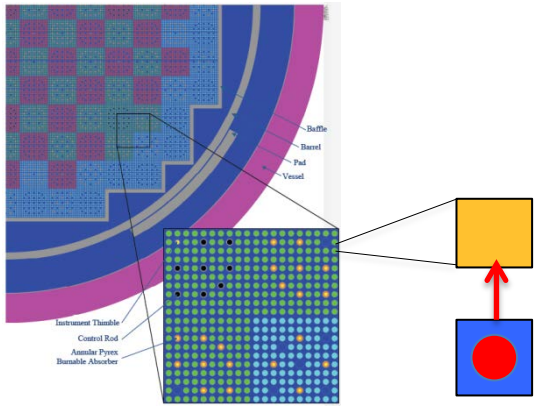
Operational time scales: hours to days to years to decades
Safety time scales: sec to min to hours to days

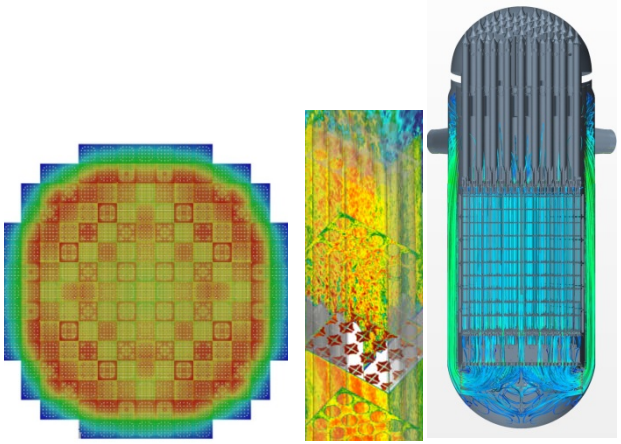
HPC Roadmaps Offer Game-Changing Opportunities

Example : coupled-Physics Core Simulations

Terascale	Petascale	Exascale
***Engineering** Analysis*	***High-Fidelity** Core Analysis*	***Extreme-Fidelity** Analysis*
• Criticality and safety set-points • Core power predictions • Cycle fuel depletions • Transient safety analysis • Core loading optimization • Operator-assist predictions • Real-time operator training simulators	• Criticality and safety set-points • Core pin power predictions • Cycle isotopic fuel depletions • Localized sub-channel feedback • Assembly or full core structural models	• Azimuthal/radial intra-pellet isotopics • Rim effects in high burnup fuel pins • Localized CRUD deposition//corrosion • Fluid/structure vibrations/wear • Physics-based DNBR predictions • Vessel flow asymmetry and instabilities • Fully coupled TH/structural full core







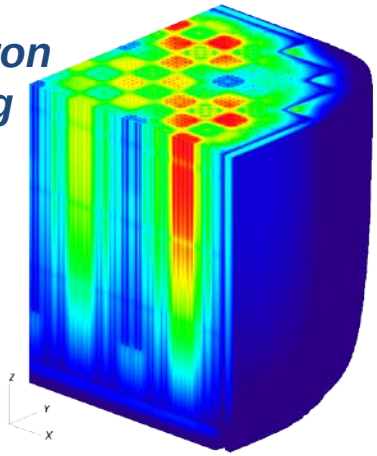
Homogenized Fuel Assemblies	*Homogenized Fuel Pin-Cells*	*Explicit Fuel/Clad/Fluids &Vessel*
• Pre-computed assembly data tables • Few-group nodal diffusion neutronics • Characteristic-channel fuel pin • Characteristic-channel thermal fluids • Macroscopic fuel assembly depletion • Lumped-parameter closure relations	• Pre-computed pin-cell data tables • Multi-group transport neutronics • Simplified explicit-pin fuel mechanics • Sub-channel and CFD thermal fluids • Microscopic fuel pin depletion • Simplified-physics closure relations	• No pre-computed data tables • Continuous-energy Monte Carlo • Meso/macro fuel pin mechanics • CFD and DNS thermal fluids • Intra-pellet isotopics in fuel depletion • Physics-based closure relations

M&S Solutions Realizable at the Petascale

A Step Change in Technology

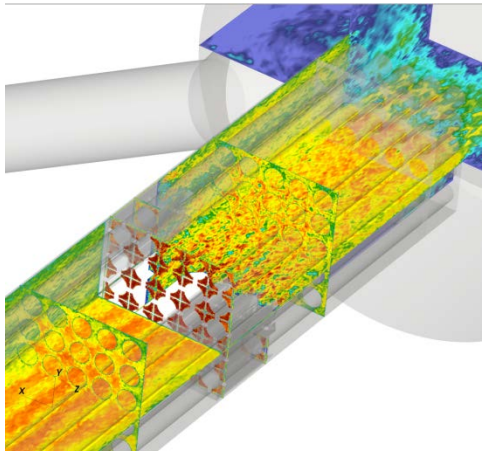
Predictive full core neutron state points for operating reactors

- Consistent method for 3D pin-resolved deterministic and Monte Carlo transport



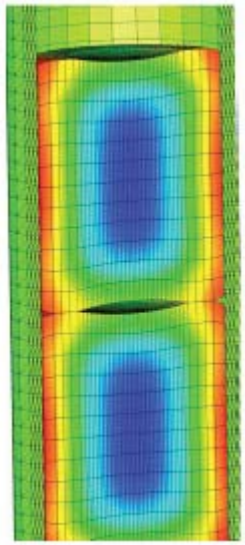
Calibrated CFD of full core turbulent multi-phase flows

- With boiling and upscaled closure models, mechanistic DNB assessment



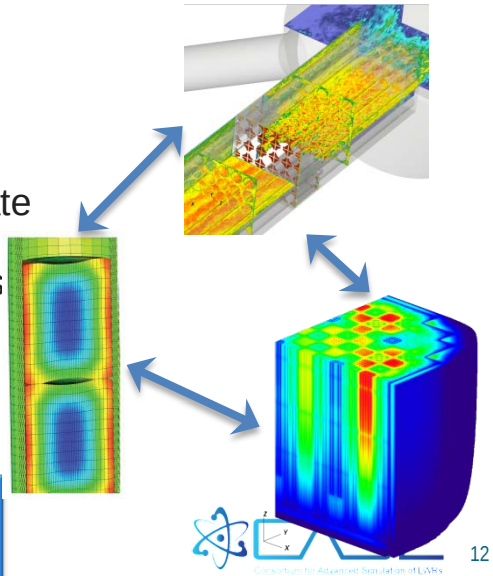
Reliable 3D assessment of nuclear fuel performance

- Inform assessments of operational risks & identify solutions (PCI,CRUD)
- Functional capability for fuel response in reactor transients (RIA, LOCA)



Identify vulnerabilities to operational & safety performance-limiting reactor phenomena

- Tightly-coupled multi-physics assessment of system performance
- Understand best-estimate system response and associated uncertainties upset events

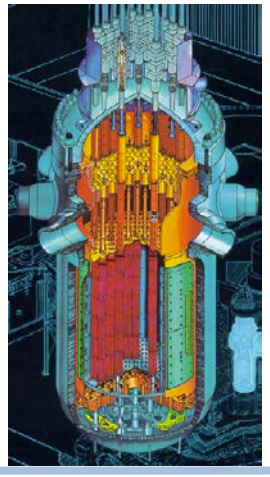


Leapfrogs calibrated industry core simulators that use lumped homogenization & correlation based closures

M&S Solutions Expected at the Exascale

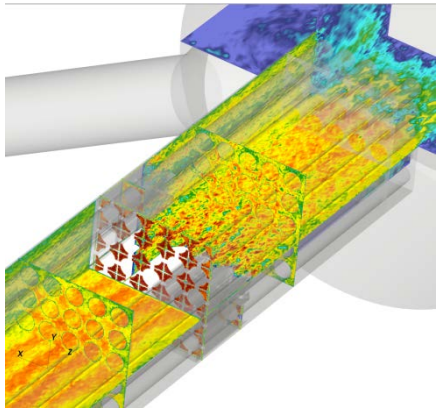
Reactor Core Physics

- **Predictive load-follow simulation for feedback to operational reactors for plant maneuvering and upset event recovery**
  - Core-wide multi-physics: radiation transport, fluids, fuels, chemistry, material, local wear and contacts, full core structural response
- **Expand to entire power plant**



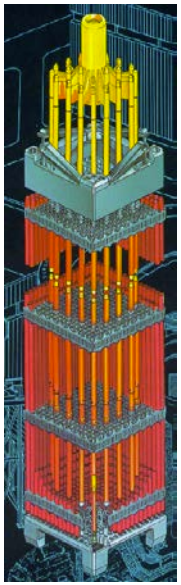
Thermal Hydraulics

- **Enhanced heat transfer from fuel to coolant within quantified safety margins**
  - Core-wide multi-scale fluids performance with two-way DNS-to-LES CFD coupling



Nuclear Fuels

- **Investigation and suppression of barriers to higher fuel burnup**
  - Micro-scale informed fuel behavior and transient transport
- **Reliable, targeted fuel designs outside of principal test base**
  - Multi-scale fuel performance (active two-way coupling micro to meso to macro)
- **Fuel failure prediction**
  - Move from empirical failure thresholds to mechanistic models of actual failure

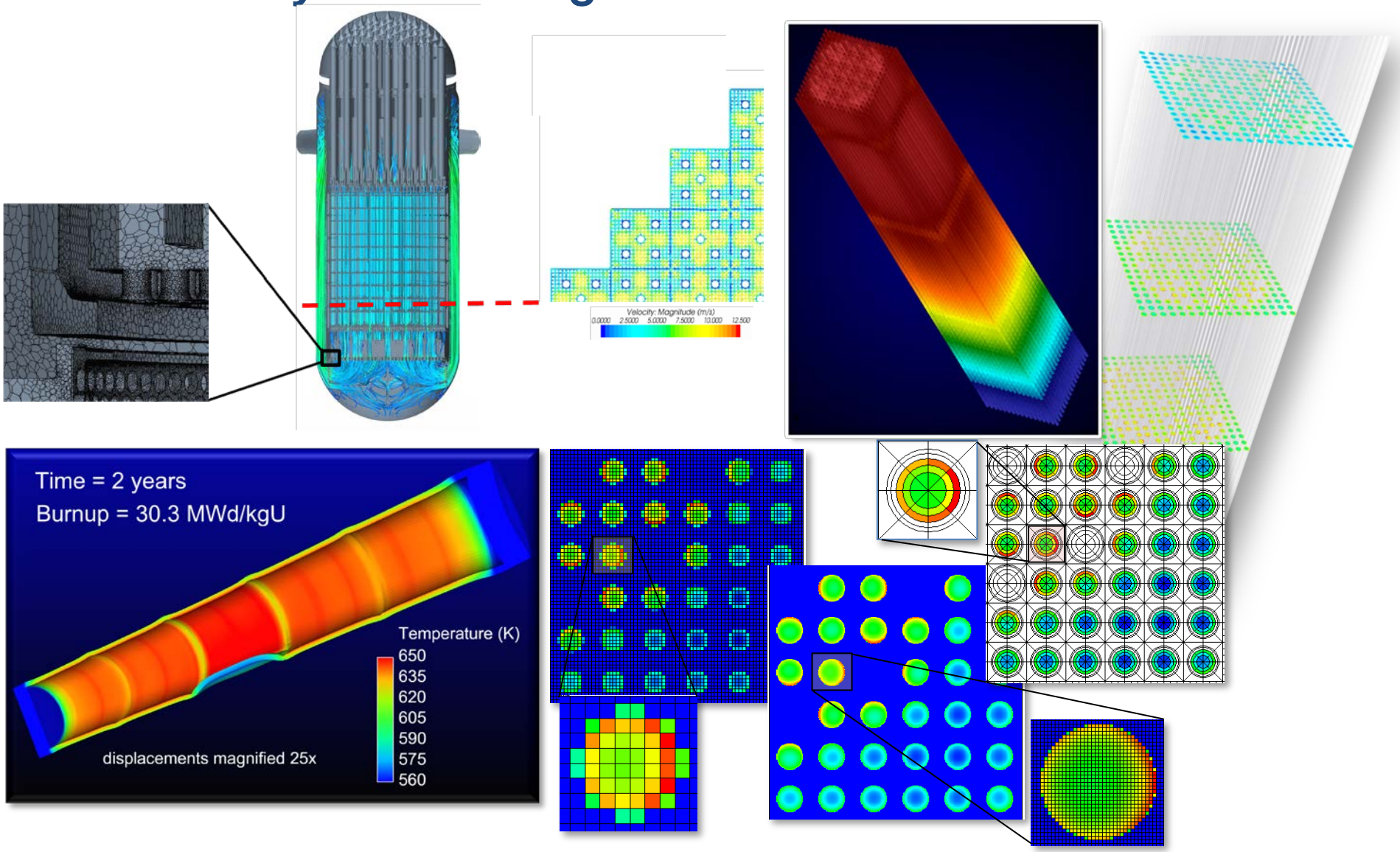


V&V, Data Assimilation & UQ

- **Execution of quality virtual experiments to fill validation data gaps**
  - Computational (pseudo experimental) data generated by full resolution core simulator used for data assimilation & UQ of design tools
- **Optimum experimental design & usage**
  - Integrated data assimilation, UQ & mathematical optimization to design experiments & process resulting data to recover margins to safety & operational limits

Underpinned by enabling science-based engineering models

M&S R&D Must Meet the Multi-Scale Challenge of Predictively Simulating a Reactor Core

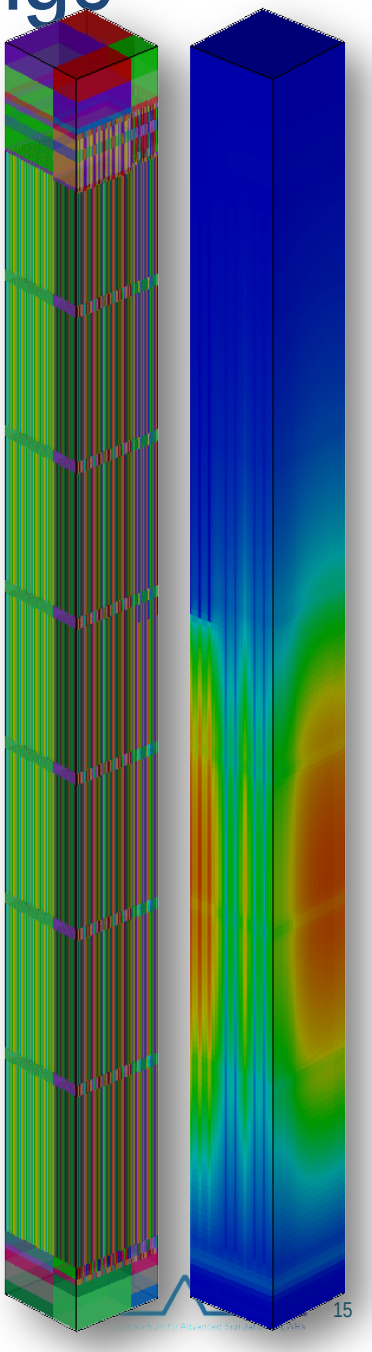


From full core to fuel assembly to fuel subassembly to fuel pin/pellet

Strive to Impart a Technology Step Change

CASL vs. Industry Core Simulators

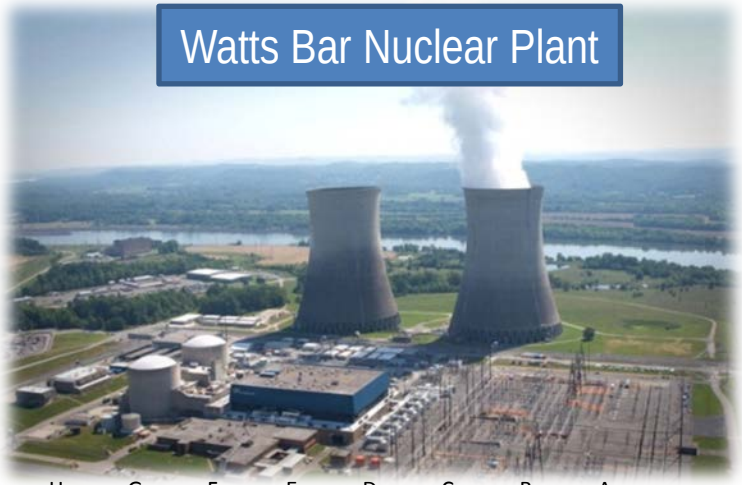
Physics Model	Industry Practice	CASL (VERA-CS)
Neutron Transport	3-D diffusion (core) 2 energy groups (core) 2-D transport on single assy	3-D transport 23+ energy groups
Power Distribution	nodal average with pin-power reconstruction methods	explicit pin-by-pin
Thermal-Hydraulics	1-D assembly-averaged	subchannel (w/crossflow)
Fuel Temperatures	nodal average	pin-by-pin 2-D or 3-D
Xenon/Samarium	nodal average w/correction	pin-by-pin
Depletion	infinite-medium cross sections quadratic burnup correction history corrections spectral corrections reconstructed pin exposures	pin-by-pin with actual core conditions
Reflector Models	1-D cross section models	actual 3-D geometry
Target Platforms	workstation (single-core)	1,000 – 300,000 cores



CASL current and planned capabilities will leapfrog calibrated industry core simulators that use lumped homogenization and correlation-based closures

VERA Modeling Comparisons to Plant Measurements: Zero Power Physics Tests

- TVA's Watts Bar Nuclear Unit 1 is CASL's "physical" reactor
- Recently modeled the zero power physics tests performed at start up of the reactor (Cycle 1)
- Zero Power Physics Tests are performed at the startup of each operation cycle to confirm the the core had been loaded correctly and that control rod worth meets safety requirements
- Goal of analysis is to predict critical configurations, control rod worth, differential boron absorber worth and isothermal temperature coefficients.



	H	G	F	E	D	C	B	A
8	2.1	2.6 20	2.1	2.6 20	2.1	2.6 20	2.1	3.1 12
9	2.6 20	2.1	2.6 24	2.1	2.6 20	2.1	3.1 24	3.1
10	2.1	2.6 24	2.1	2.6 20	2.1	2.6 16	2.1	3.1 8
11	2.6 20	2.1	2.6 20	2.1	2.6 20	2.1	3.1 16	3.1
12	2.1	2.6 20	2.1	2.6 20	2.6	2.6 24	3.1	
13	2.6 20	2.1	2.6 16	2.1	2.6 24	3.1 12	3.1	
14	2.1	3.1 24	2.1	3.1 16	3.1	3.1		
15	3.1 12	3.1	3.1 8	3.1				

Enrichment
Number of Pyrex Rods

Cycle 1 Core Loading

VERA (CASL) Results for Watts Bar Unit 1 Startup Critical Configurations

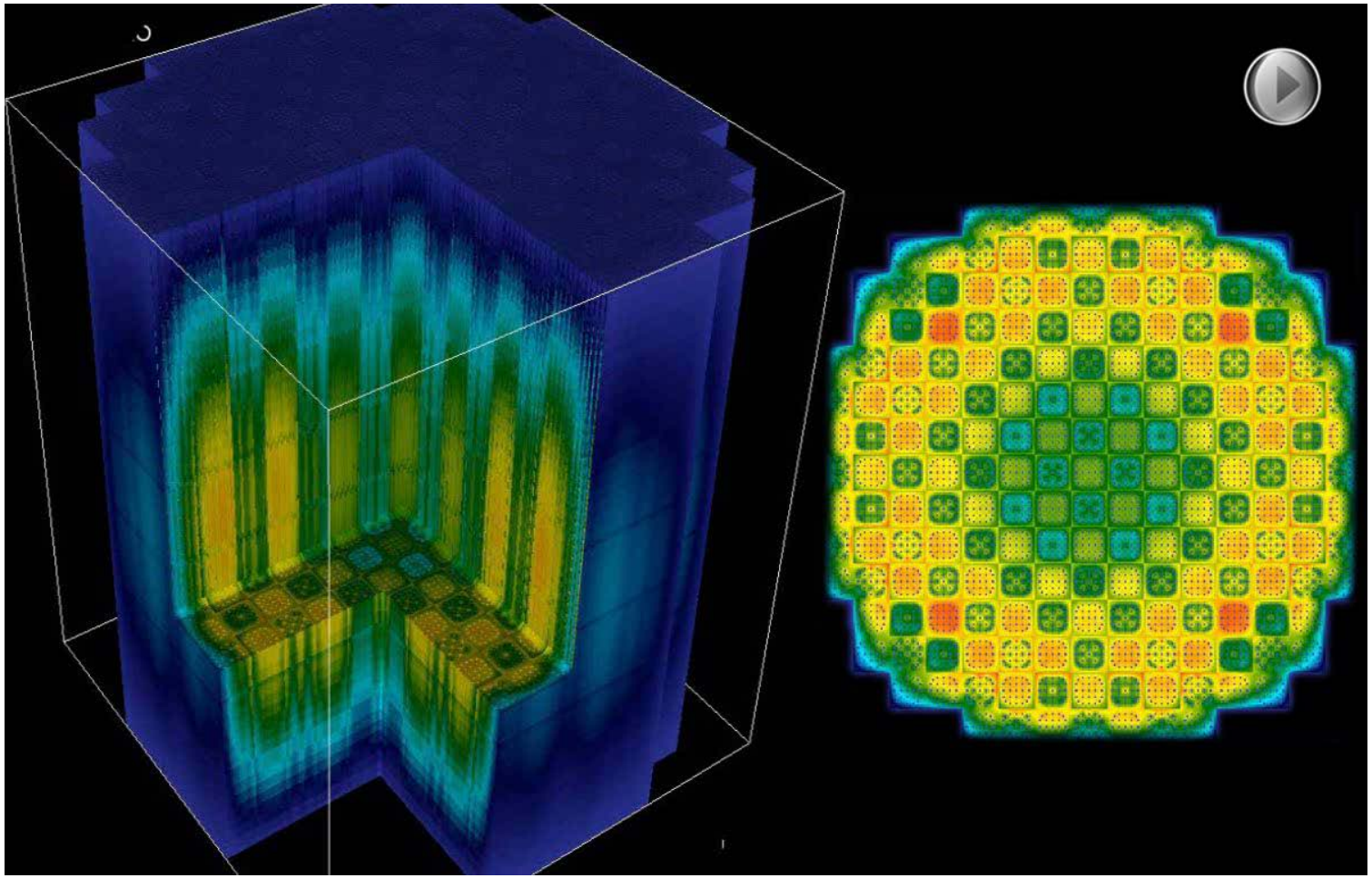
Critical Configuration	VERA k-eff	Difference (pcm)
Initial	1.00122	122
ARO	1.00157	157
Bank D In	1.00084	84
Bank C In	1.00094	94
Bank B In	1.00081	81
Bank A In	1.00092	92
Bank SD In*	1.00073	73
Bank SC In*	1.00071	71
Bank SB In	1.00100	100
Bank SA In	1.00070	70
Average	**1.00094**	**94**
St. Deviation	**0.00027**	**27**

Control Rod Bank Locations

	H	G	F	E	D	C	B	A
8	D		A		D		C	
9						SB		
10	A		C				B	
11				A		SC		
12	D				D		SA	
13		SB		SD				
14	C		B		SA			
15								

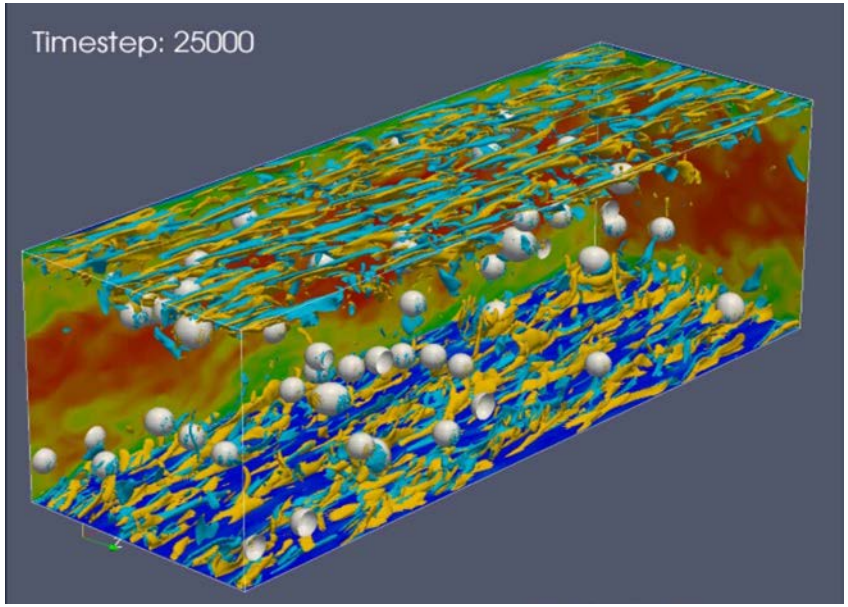
Excellent Agreement with Plant Conditions (keff = 1)

Simulation Opportunities: Full Core, Pin-Resolved Reactor Physics

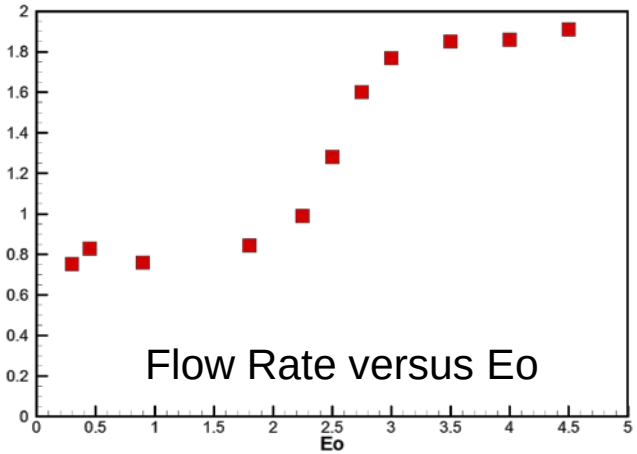


Simulation Opportunities: Changing Modeling of Unresolved Phenomena in a Fundamental Way

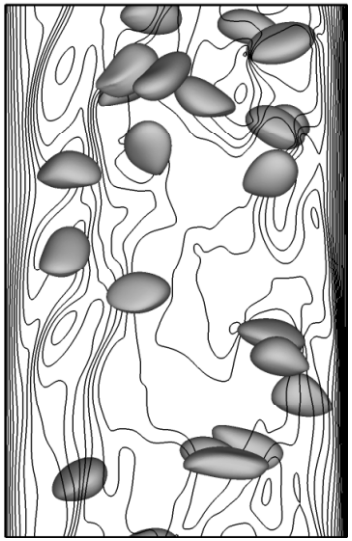
- Permits direct computation of modeled terms at given points in space/time and to assess their mean and fluctuation components
- Approach in single-phase flows has led to significant advances in understanding and developing closure models
- Provides the foundations for more complete multiphase CFD turbulence modeling
- Developing a DNS lift/drag database for integral momentum closure model



Bubble Deformability Effects



High Eo



We Can Now Achieve Unimaginable Resolution

How to make the "best" use of it?

Purpose

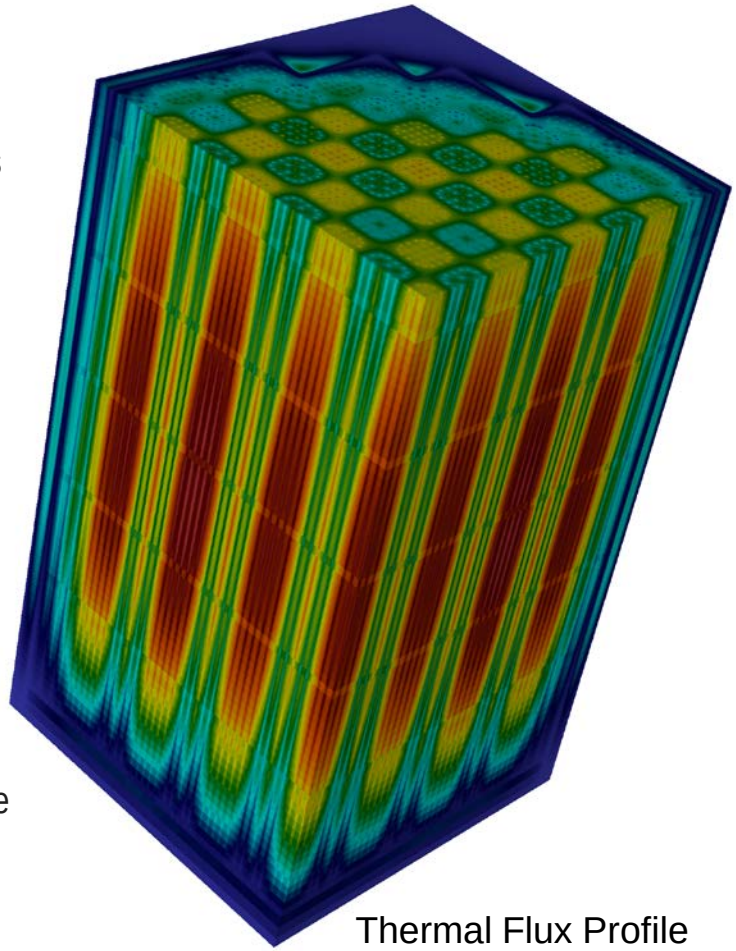
- First large-scale coupled multi-physics model of operating PWR reactor using Components of CASL's Virtual Environment for Reactor Applications (VERA)
- Features resolved are based on the dimensions and state conditions of Watts Bar Unit 1 Cycle 1: geometry for fuel, burnable absorbers, spacer grids, nozzles, and core baffle

Execution

- Common input used to drive all physics codes
- Multigroup neutron cross sections calculated as function of temperature and density (SCALE/XSPROC)
- SP_N neutron transport used to calculate power distribution (DENOVO)
- Subchannel thermal-hydraulics in coolant (COBRA-TF)
- Rod-by-Rod heat conduction in fuel rods (COBRA-TF)
- Simulation ran in 17.5 hours on Titan using 18,769 cores – over 1M unique material (fuel/coolant/internals) regions resolved

Next Steps

- Add fuel depletion and core shuffling
- Compare results to plant measured data



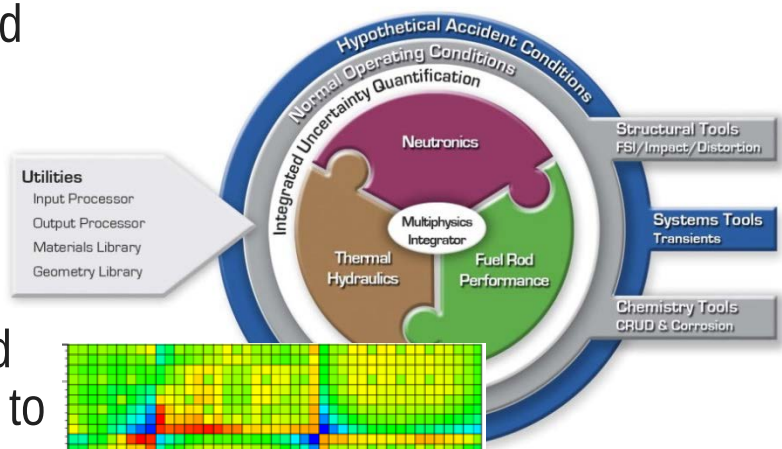
Thermal Flux Profile in Reactor Core

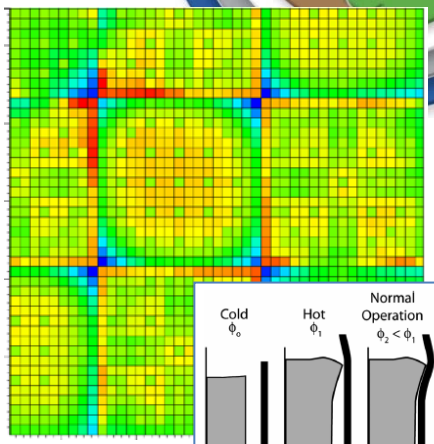
"Demonstration of Neutronics Coupled to Thermal-Hydraulics for a Full-Core Problem using VERA", CASL-U-2013-0196-000, Dec 2013.

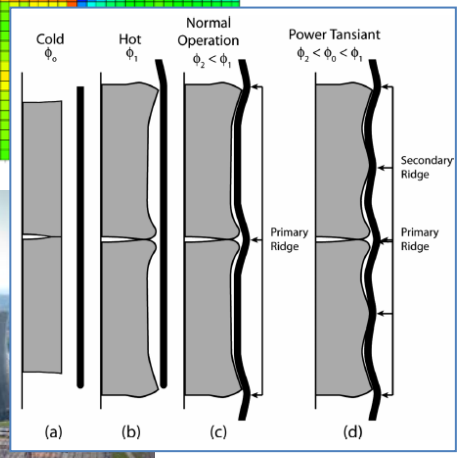
Aggressively Deploy, Deploy, Deploy . . .

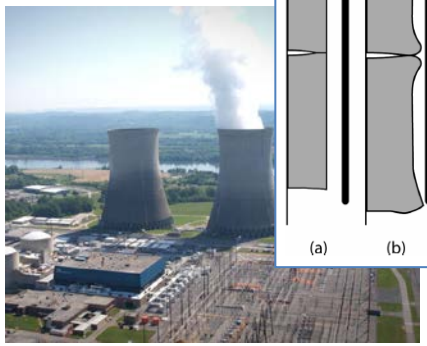
From Pilot Projects to Test Stands to Beta Releases to Broad Releases

- U.S. taxpayers investment in CASL will only be realized if its products are deployed beyond the labs and the core CASL team to the broader nuclear industry
- Pilot Projects: simulation applications of VERA outside of direct CASL scope yet of interest to industry
- Test Stands: Early deployment to industry for rapid and enhanced testing, use, and ultimate adoption of VERA to support real-world LWR applications
  - WEC: Deployment Mar 2013; focus on VERA simulation of AP1000 first core startup
  - EPRI: Deployment Nov 2013; new EPRI computing capabilities will be utilized to test fuel performance (Peregrine) performance applications
  - TVA: Deployment planned for Mar 2014; focus currently targeted for lower plenum flow anomaly observed in many current operational reactors









VERA Test Stand at Westinghouse: AP1000® Zero Power Physics Tests Simulation

- Purpose: Initial deployment of VERA-CS
  - Public report available
- Results: Excellent agreement with KENO
  - Some differences in ITC & MTC

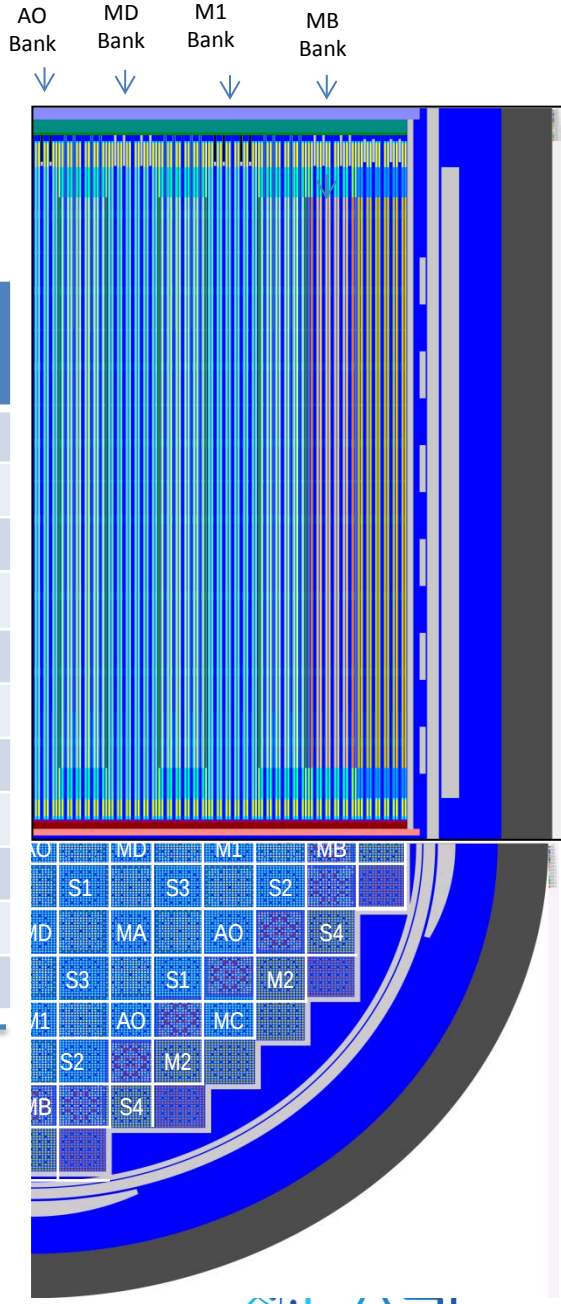
Start-up Boron and Reactivity Coefficients

	KENO	VERA
Critical Boron (ppm)	1314	1311
Isothermal Temp. Coeff. (pcm/F)	-2.7	-3.2
Doppler Temp. Coeff.	-1.6	-1.7
Moderator Temp. Coeff.	-1.1	-1.5

Control Rod Worth

	KENO	VERA-KENO (pcm)	VERA-KENO (%)
MA	258	-1	-0.5
MB	217	-5	-2.1
MC	188	-2	-1.1
MD	234	0	0.0
M1	651	-4	-0.6
M2	887	3	0.4
AO	1635	-4	-0.3
S1	1079	0	0.0
S2	1096	-9	-0.8
S3	1124	0	0.0
S4	580	-3	-0.4

KENO Model



Highlights of AP1000 Test Stand Results

Start-up Boron and Reactivity Coefficients

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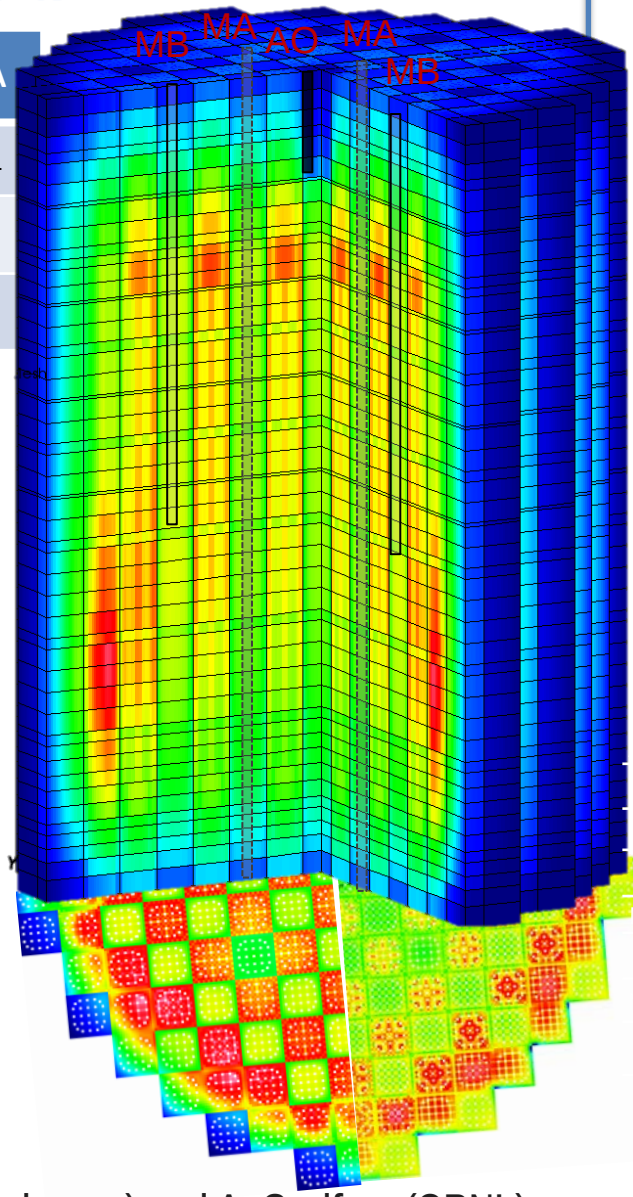
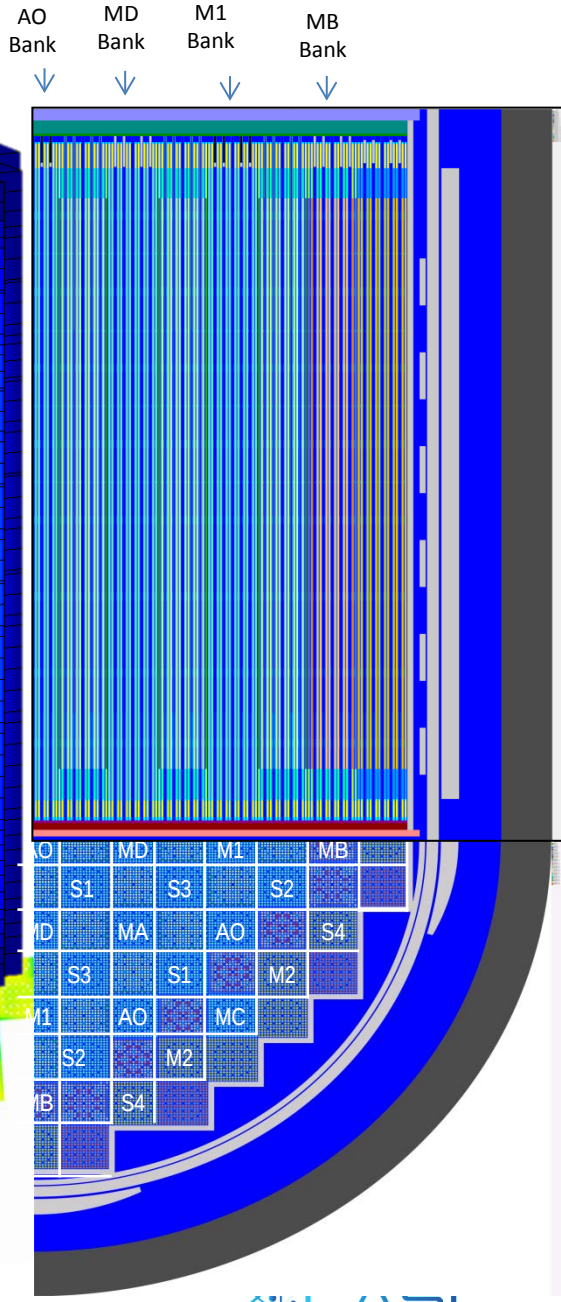
Power Distribution



AP1000 Core KENO Model



Main Contributors: F. Franceschini (Westinghouse) and A. Godfrey (ORNL)

Evaluate New VERA Continuous-Energy Monte Carlo Capability (Shift) – Quarter-Core Zero Power Physics Test

Goals

- Compare fidelity and performance of Shift against Keno, SP_N, and S_N (Denovo)
- Generate high-fidelity neutronics solution for code comparison of solutions for predicting reactor startup and physics testing

Contributors

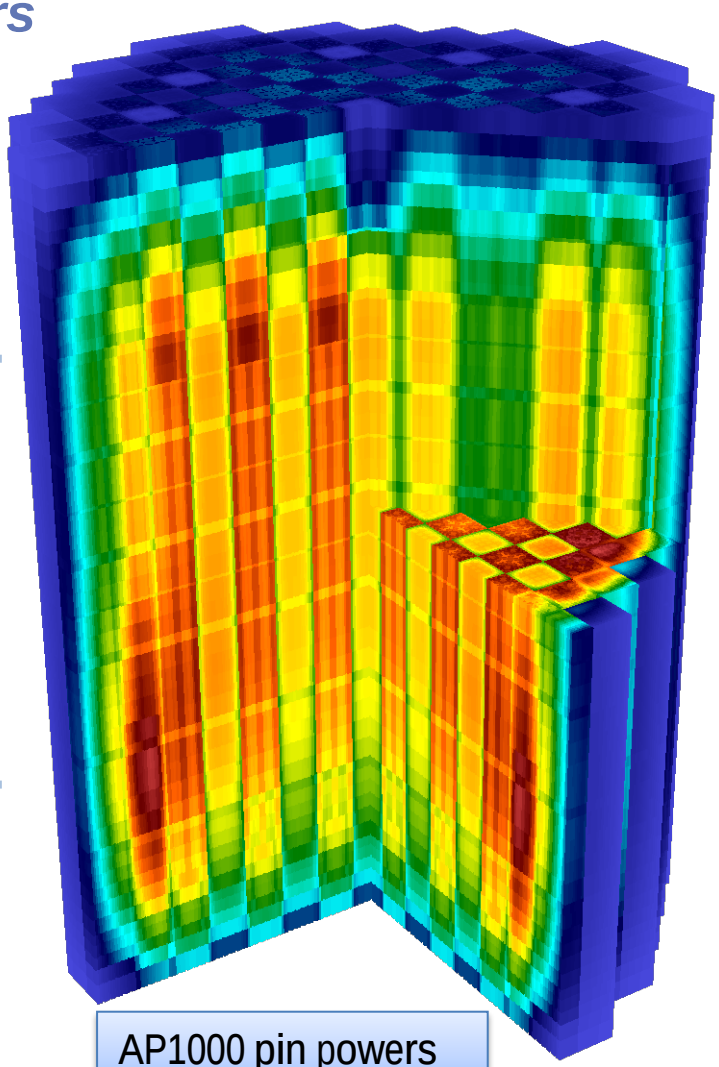
Tom Evans
Fausto Franceschini
Andrew Godfrey
Steve Hamilton
Wayne Joubert
John Turner

Execution

- Proposal submitted to OLCF as part of Titan Early Science program
- Awarded 60 million core-hours on Titan (worth >$2M)
- AP1000 model created and results generated for reactor criticality, rod worth, and reactivity coefficients
- Identical VERA Input models used for Shift, SP_N, and S_N
  - dramatically simpler than KENO-VI input model

Results

- Some of the largest Monte Carlo calculations ever performed (1 trillion particles) have been completed
  - runs use 230,000 cores of Titan or more
- Excellent agreement with KENO-VI
- Extremely fine-mesh S_N calculations, which leverage Titan's GPU accelerators, are under way



AP1000 pin powers

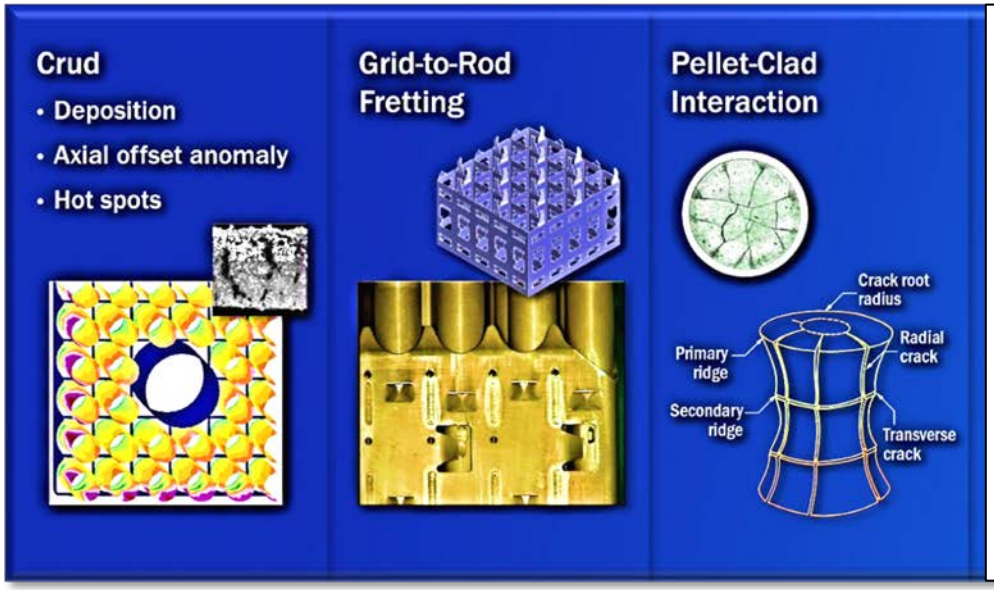
Undertake the Right *Industry Challenge Problems*

Tackle key safety-relevant reactor phenomena that limit performance

Safety Related Challenge Problems

CASL Challenge Problems

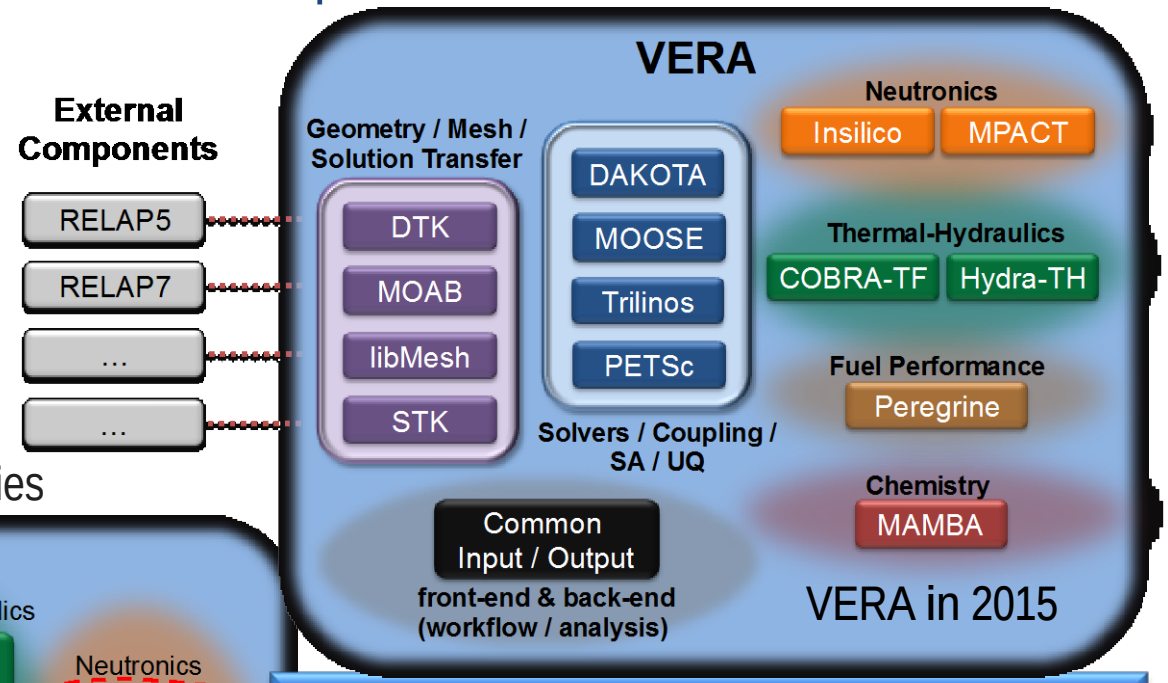
- Are relevant industry problems whose solutions remain elusive
- Are amenable to insight afforded by advanced M&S
- Help to direct RD&D activities on CASL M&S technology
- Help to establish clear performance metrics



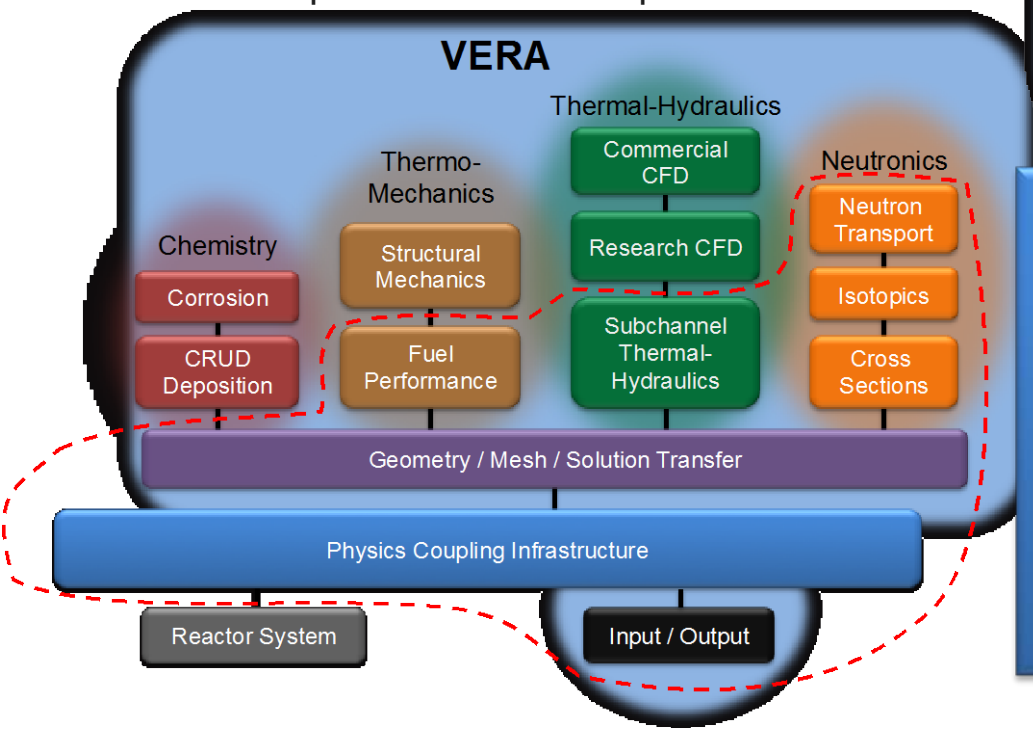
Operational Challenge Problems

VERA: Virtual Environment for Reactor Applications

CASL's evolving virtual reactor for in-vessel LWR phenomena



Required functional capabilities



CASL has 3 M&S technology products

1. VERA-CS as the fast running core simulator, which has value both standalone and for providing power histories, etc for more detailed codes
2. Engineering suite of standalone codes with ability to couple 2 or more within VERA or in other environments
3. Leadership suite of high fidelity codes used to drive improvements in 1 and 2

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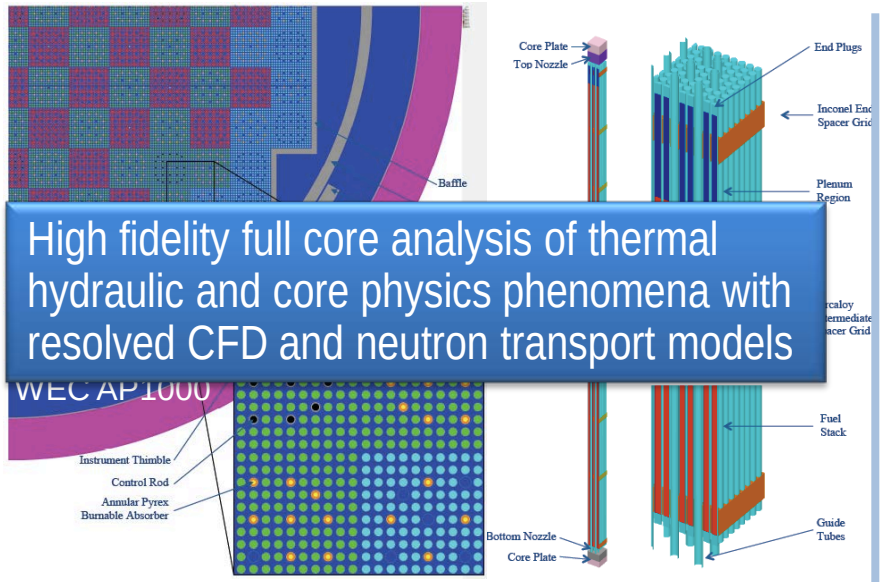
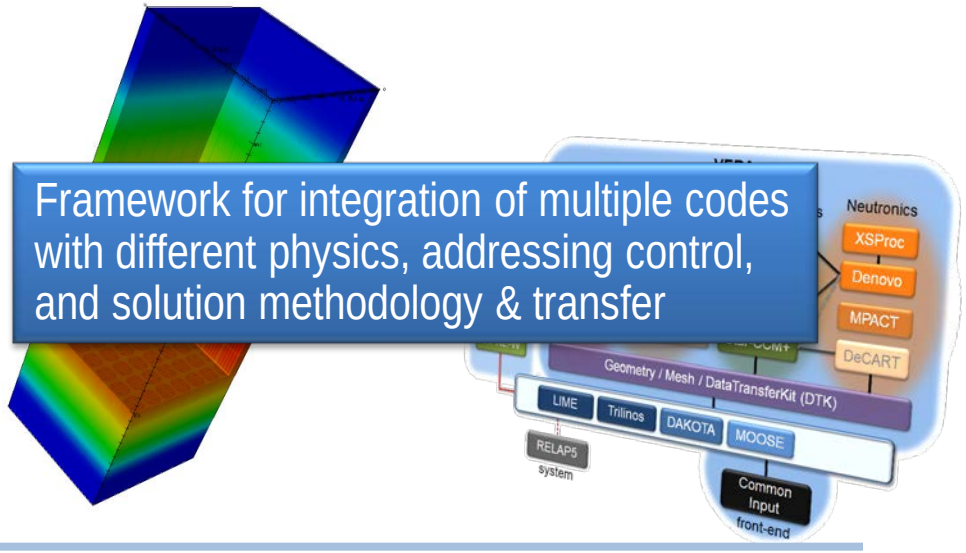
CASL Innovations

Advanced Modeling Applications



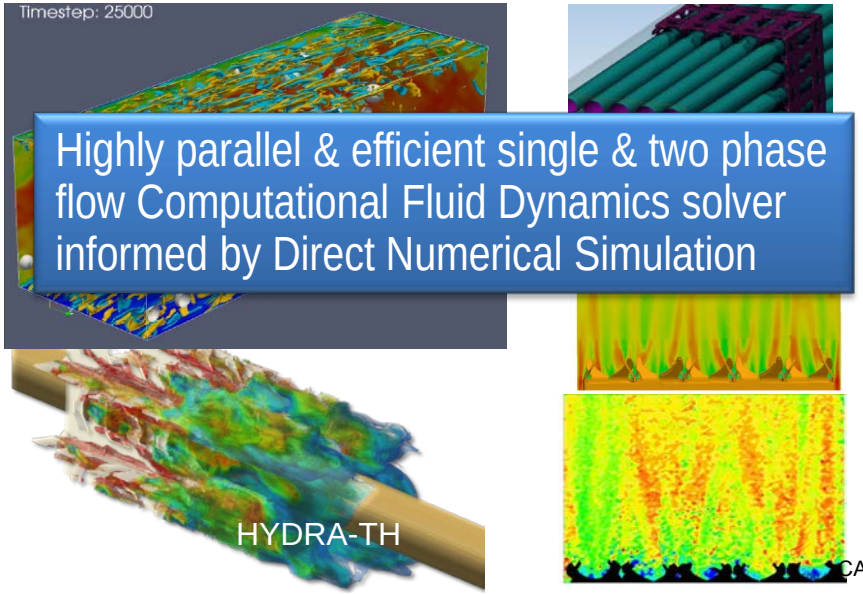
High fidelity full core analysis of thermal hydraulic and core physics phenomena with resolved CFD and neutron transport models

Physics Integration



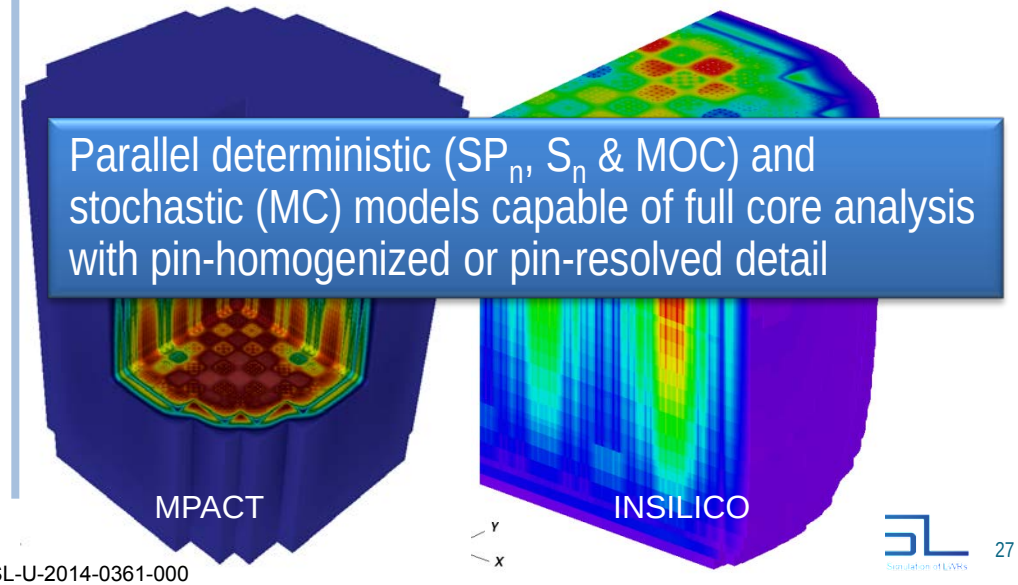
Framework for integration of multiple codes with different physics, addressing control, and solution methodology & transfer

Thermal Hydraulic Methods



Highly parallel & efficient single & two phase flow Computational Fluid Dynamics solver informed by Direct Numerical Simulation

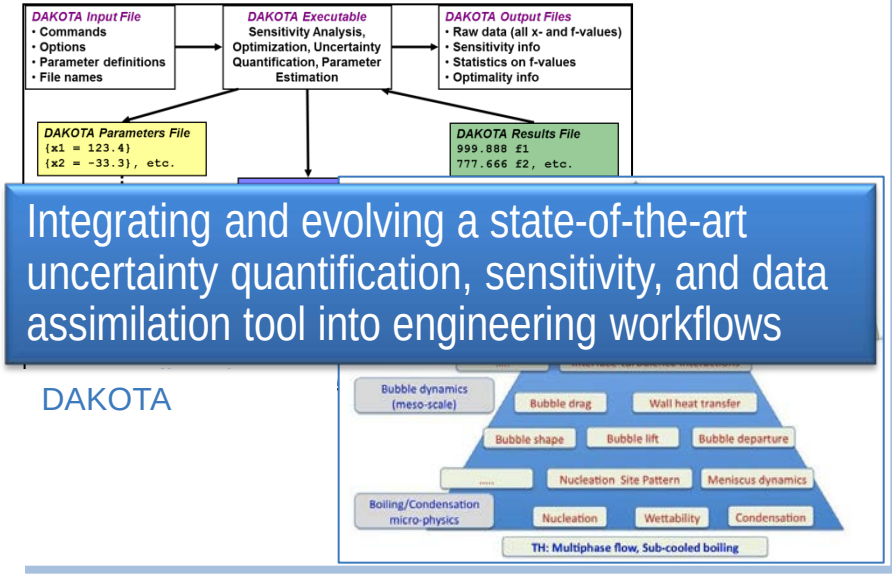
Radiation Transport Methods



Parallel deterministic (SP_n, S_n & MOC) and stochastic (MC) models capable of full core analysis with pin-homogenized or pin-resolved detail

CASL Innovations

Validation & Uncertainty Quantification



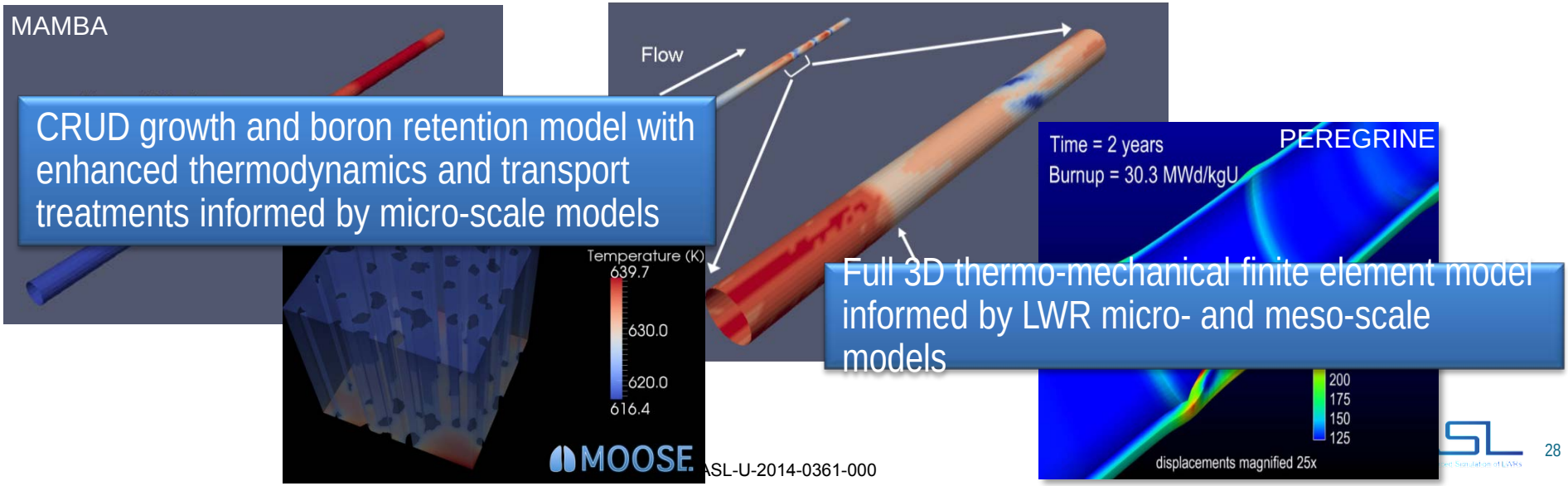
Integrating and evolving a state-of-the-art uncertainty quantification, sensitivity, and data assimilation tool into engineering workflows

DAKOTA

VOCC

Bringing together local ("physical") and geographically distributed ("virtual") contributors in a meaningful and productive way

Materials Performance and Optimization



CRUD growth and boron retention model with enhanced thermodynamics and transport treatments informed by micro-scale models

Full 3D thermo-mechanical finite element model informed by LWR micro- and meso-scale models

Proactively Engage Industry

Assure that R&D solutions are "used and useful" by industry and while advancing the M&S state-of-the-art.

CASL Industry Council: Objectives and Strategies

- Early, continuous, and frequent interface and engagement of end-users and technology providers
- Critical review of CASL plans and products
- Optimum deployment and applications of periodic VERA releases
- Identification of strategic collaborations between industry and CASL Focus Areas

Outcomes and Impact

- CASL benefits from advice on technical requirements, schedules, commercialization strategies, and computer requirements
- Industry Council can influence the CASL product to be compatible with expected applications and can better prepare internal technical and business processes

Be Sure to Implement/Integrate Education and Training

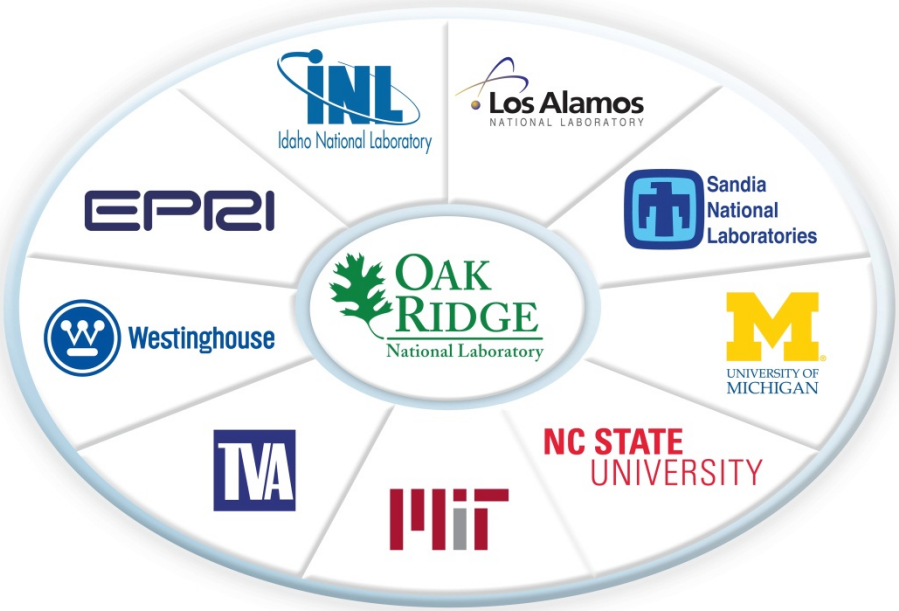
CASL Education Program

- Facilitate transfer of CASL technology into the class room and to the nuclear industry
  - CASL Educational Modules
    - Cross-university offering of educational materials (Neutronics, Thermal Hydraulics, Fuel Performance, UQ)
  - CASL Webinar Series
  - CASL Graduate Student Summer Workshops (2011 – present)
  - CASL School (Summer 2015)
    - For graduate students and industry - intensive applications of CASL Education Modules
- Development of an “Educational/Production” version of VERA that is amenable to University instruction
  - Transparent user interface (in development)
  - Reasonable run times on student/utility assessable platforms
- Educating faculty to benefits of using VERA
- VERA training to industry (with Industry Council)

CASL-U-2014-0361-000

What are the basic research challenges, opportunities, and needs for advanced nuclear energy systems?

- ✓ *Needs: Get the R&D management construct right*
  - *Clear deliverables that solve industry issues and are driven by a well-defined plan*
  - *A strategy of delivering prototype products early and often*
  - *Defined customers and users, with "industry pull" ensured by an industry council*
  - *A true private-public partnership in management, leadership, and execution*
  - *Short (5-year?) horizon for completion*
  - *Ensure oversight and advice on management, planning, and science & technology strategies*
  - *Independent councils to review and advise on quality and relevance of S&T*
- ✓ *Opportunities: advanced M&S technologies are the "right thing at the right time"*
  - *Move nuclear energy from leader to follower*
- ✓ *Challenges*
  - *Working within regulatory environment – very doable but is definitely a contact sport*
  - *Higher fidelity (science "deep dive") versus engineering design tool: want versus need*
  - *What is "good enough" versus "needs basic R&D"? Make sure you're chasing the right thing.*

Questions?

www.casl.gov or *info@casl.gov*